The molecular $K^*\bar{K}$ nature of the $f_1(1285)$ and its decays into $\pi a_0(980)$ ($\pi f_0(980)$) and $\pi K\bar{K}$

Francesca Aceti

Instituto de Física Corpuscular, Universidad de Valencia - CSIC

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Co-authors:

J. M. Dias, Ju-Jun Xie and E. Oset

Outline

F. A, Ju-Jun Xie, E. Oset, arXiv:1505.06134 [hep-ph]
F. A. J. M. Dias, E. Oset, Eur. Phys. J. A51 (2015) 48

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  - formalism
  - results for the decay width
  - invariant mass distributions
- $f_1(1285) \to \pi K\bar{K}$ and isospin breaking
  - formalism
  - results for the decay width
  - invariant mass distributions
- conclusions

Introduction

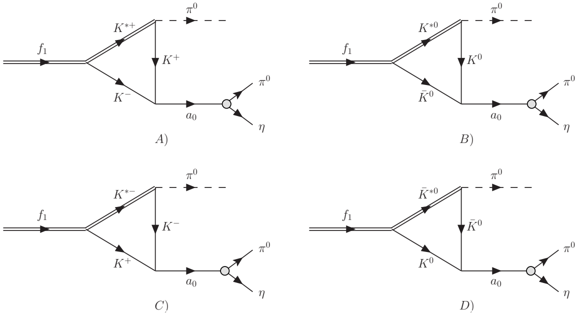
starting point $\longrightarrow$ **$f_1(1285)$, $a_0(980)$ and $f_0(980)$ are dynamically generated by meson-meson interaction**

- **$f_1(1285)$**
  - $0^+(1^{++})$
  - appears in the pseudoscalar-vector interaction
  - it comes from the single channel $K^*\bar{K} - c.c.$ [Roca et al., Phys. Rev. D 72, 014002 (2005)]
- **$a_0(980)$**
  - $1^-(0^{++})$
  - appears in the pseudoscalar-pseudoscalar interaction
  - building blocks: $\pi\eta$, $K\bar{K}$ [Oller et al., Nucl. Phys. A 620, 438 (1998)]
- **$f_0(980)$**
  - $0^+(0^{++})$
  - appears in the pseudoscalar-pseudoscalar interaction
  - building blocks: $\pi\pi$, $K\bar{K}$ [Oller et al., Nucl. Phys. A 620, 438 (1998)]

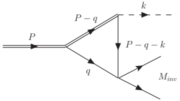
$f_1(1285) \to a_0(980)\pi$ decay: formalism

- $\boldsymbol{B.R.(f_1(1285) \to a_0(980)\pi) = (36 \pm 7)\%}$ excluding $\boldsymbol{a_0(980) \to K\bar{K}}$
  [Particle Data Group, Chin. Phys. C, 38, 090001 (2014)]

- dynamically generated picture $\Longrightarrow$ the process is described by the **triangular diagrams**:

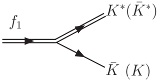


Momenta assignment:



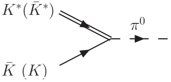
$f_1(1285) \to a_0(980)\pi$ decay: formalism

Vertices:



$$-it_1 = -ig_{f_1}\, C_1 \epsilon^\mu \epsilon'_\mu$$

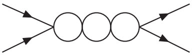
- $g_{f1} = 9687$ MeV, evaluated as the residue at the pole of $T = [1 - VG]^{-1} V$ for $K^* \bar{K} - c.c.$ in $I = 0$
  [the potential V is taken from Roca et al., Phys. Rev. D 72, 014002 (2005)]
- the loop function G is regularized by means of a cutoff $q_{max} \simeq 1$ GeV
- the f_1 couples to the $I = 0$, $C = +$ and $G = +$ combination of $K^* \bar{K}$:
  $-\frac{1}{2}(K^{*+}K^- + K^{*0}\bar{K} - K^{*-}K^+ - \bar{K}^{*0}K^0)$



$$-it_2 = -igC_2(2k - P + q)^\mu \epsilon'_\mu$$

- Hidden Gauge VPP Lagrangian $\mathcal{L}_{VPP} = -ig\langle V^\mu [P, \partial_\mu P]\rangle$ [Phys. Rev. Lett. 54, 1215 (1985)]
- $g_v = \frac{m_V}{2f}$, $m_V \simeq m_\rho$, $f = 93$ MeV

$f_1(1285) \to a_0(980)\pi$ decay: formalism



$$-it_3 = -it_{if}$$

- rescattering of the $K\bar{K}$ pair
- t_{if} is the element of the 5×5 scattering matrix for the channels K^+K^- (1), $K^0\bar{K}^0$ (2), $\pi^0\eta$ (3), $\pi^+\pi^-$ (4), $\pi^0\pi^0$ (5) [Oller et al., Nucl. Phys. A 620, 438 (1998)]
- loop function regularized with a cutoff $q'_{max} = 900$ MeV

due to the physical masses of the kaons, the rescattering of $K\bar{K}$ dynamically generates the $a_0(980)$ and $f_0(980)$ leading to both $\pi^0\eta$ and $\pi^+\pi^-$ in the final state

isospin symmetry is broken

$\Longrightarrow$ simultaneous study of $f_1(1285) \to f_0(980)\pi$

$f_1(1285) \to a_0(980)\pi$ decay: formalism

Putting everything together we get, for each diagram:

$$t = C g_{f1}\, g\, \vec{\epsilon}\cdot\vec{k}\,(2\mathcal{I}_1 + \mathcal{I}_2)\, t_{if} = \tilde{t}\,\vec{\epsilon}\cdot\vec{k}\; t_{if}$$

	C_1	C_2	C
A)	$-1/2$	$1/\sqrt{2}$	$-1/2\sqrt{2}$
B)	$-1/2$	$-1/\sqrt{2}$	$1/2\sqrt{2}$
C)	$1/2$	$-1/\sqrt{2}$	$-1/2\sqrt{2}$
D)	$1/2$	$1/\sqrt{2}$	$1/2\sqrt{2}$

$$\mathcal{I}_1 = -i\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2-m_K^2+i\epsilon}\frac{1}{(P-k-q)^2-m_K^2+i\epsilon}\frac{1}{2\omega^*}\frac{1}{P^0-q^0-\omega^*+i\epsilon}$$

$$\mathcal{I}_2 = -i\int \frac{d^4q}{(2\pi)^4}\frac{1}{q^2-m_K^2+i\epsilon}\frac{1}{(P-k-q)^2-m_K^2+i\epsilon}\frac{\vec{k}\cdot\vec{q}}{|\vec{k}|^2}\frac{1}{2\omega^*}\frac{1}{P^0-q^0-\omega^*+i\epsilon}$$

- integration in dq^0 done analytically
- **integration in $d^3q \to$ upper limit naturally provided by chiral unitary approach**

the cutoff $q_{max} \simeq 900$ MeV appears automatically as upper limit in $\mathcal{I}_1$ and $\mathcal{I}_2$ thanks to the $K\bar{K} \to PP$ potential used to dynamically generate the a_0 and f_0

$$V(\vec{q},\vec{q}\,') = v\,\theta(q_{max}-|\vec{q}|)\,\theta(q_{max}-|\vec{q}\,'|)$$

$$t(\vec{q},\vec{q}\,') = t\,\theta(q_{max}-|\vec{q}|)\,\theta(q_{max}-|\vec{q}\,'|)$$

$f_1(1285) \to a_0(980)\pi$ decay: formalism

taking into account physical masses for the kaons, we can define $\tilde{t}^+$ and $\tilde{t}^0$ corresponding to $\tilde{t}$ for the case of charged and neutral kaons respectively

TOTAL AMPLITUDE OF THE PROCESSES:

$$T_{\pi^0\eta} = (2\tilde{t}^{(+)}\, t_{K^+K^-\to\pi^0\eta} + 2\tilde{t}^{(0)}\, t_{K^0\bar{K}^0\to\pi^0\eta})\, \vec{\epsilon}\cdot\vec{k} = \tilde{T}_{\pi^0\eta}\, \vec{\epsilon}\cdot\vec{k}$$

$$T_{\pi^+\pi^-} = (2\tilde{t}^{(+)}\, t_{K^+K^-\to\pi^+\pi^-} + 2\tilde{t}^{(0)}\, t_{K^0\bar{K}^0\to\pi^+\pi^-})\, \vec{\epsilon}\cdot\vec{k} = \tilde{T}_{\pi^+\pi^-}\, \vec{\epsilon}\cdot\vec{k}$$

- $\tilde{t}^+$ and $\tilde{t}^0$ have opposite signs
  [see the table for the coefficients C]
- $t_{K^+K^-\to\pi^0\eta} = -t_{K^0\bar{K}^0\to\pi^0\eta}$
  $t_{K^+K^-\to\pi^+\pi^-} = t_{K^0\bar{K}^0\to\pi^+\pi^-}$
  [Oller et al., Nucl. Phys. A 620, 438 (1998)]

$\Longrightarrow$

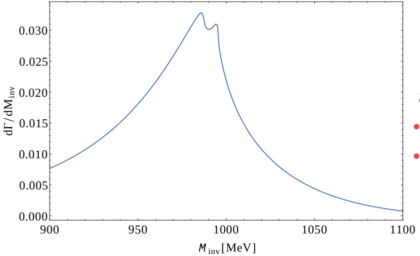
if isospin symmetry were exact ($m_{K^0} = m_{K^\pm}$) $T_{\pi^+\pi^-} \equiv 0$ and the production of the f_0 would be forbidden

isospin symmetry is not exact $\longrightarrow$ we can have both the $\pi^0\eta$ and $\pi^+\pi^-$ pairs in the final state

$f_1(1285) \to a_0(980)\pi$ decay: results

We plot the invariant mass distribution for both cases:

$$\frac{d\Gamma}{dM_{inv}} = \frac{1}{(2\pi)^3}\frac{p_\pi |\vec{k}|}{4m_{f1}^2}\frac{1}{3}|\tilde{T}|^2$$

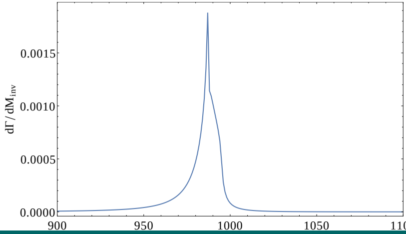


$f_1(1285) \to \pi^0\pi^0\eta$

- $a_0(980)$ produced with its normal width $\simeq 50$ MeV
- high strength at the peak

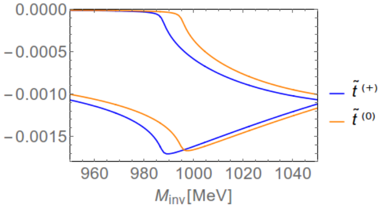
$f_1(1285) \to \pi^0\pi^+\pi^-$

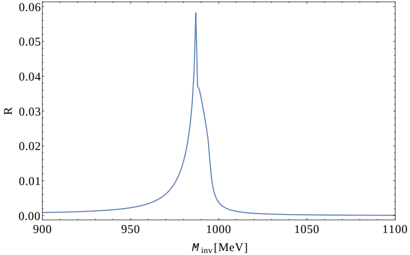
- narrow peak, width $\simeq 10$ MeV
  in agreement with BESIII recent observations
  [arXiv:1505.06283 [hep-ex]]
  in agreement with what found in other reactions like $\eta' \to \pi^0\pi^+\pi^-$
  [BES, Phys. Rev. Lett. 108,182001 (2012)]
- the peak is between the two K^+K^- and $K^0\bar{K}^0$ thresholds



$f_1(1285) \to a_0(980)\pi$ decay: results

due to the fact that the difference between $|\tilde{t}^+|$ and $|\tilde{t}^0|$ is significant only between the two thresholds





ratio of strength at the peak $\simeq 6\%$
ten times smaller than what we got in the case of the $\eta' \to \pi^0\pi^0\eta, \pi^0\pi^+\pi^-$
[Phys. Rev. D 86,114007 (2012)]

the amount of isospin breaking depends on the reaction but can give important informations on the nature of the resonances involved

$f_1(1285) \to a_0(980)\pi$ decay: results

PARTIAL WIDTH FOR THE DECAY TO $a_0\pi$:

$$\Gamma_{a_0\pi} = 3 \int dM_{inv} \left(\frac{d\Gamma}{dM_{inv}}\right)_{\pi^0\eta} = 7.6 \text{ MeV}$$

$$BR(f_1 \to a_0\pi)|_{exp} = (36 \pm 7)\%$$

$$BR(f_1 \to a_0\pi)|_{th} \simeq 31\%$$

Two sources of **uncertainties**:

- cutoff used for the generation of the $f_1(1285)$: we change it of ± 20 MeV $\to$ variation of $\Gamma_{a_0\pi}$ of 2.5%
- cutoff used in $\mathcal{I}_1$ and $\mathcal{I}_2$: we change it of ± 20 MeV $\to$ variation of $\Gamma_{a_0\pi}$ of 1.5%

$$\boxed{BR(f_1 \to a_0\pi)|_{th} = (31.4 \pm 1.2)\%}$$

We also get: $\frac{\Gamma(\pi^0 f_0(980))}{\Gamma(\pi^0 a_0(980))} = 1.28 \times 10^{-2}$

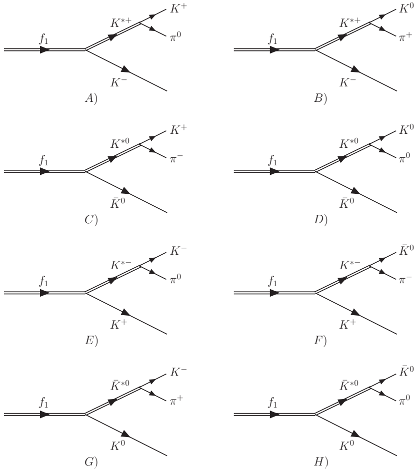
much smaller than $\frac{\Gamma(\eta(1405) \to \pi^0 f_0(980))}{\Gamma(\eta(1405) \to \pi^0 a_0(980))} = 18 \times 10^{-2}$ [BESIII, Phys. Rev. Lett. 108,182001 (2012)]

and twice as big as $\frac{\Gamma(J/\psi \to \phi f_0(980))}{\Gamma(J/\psi \to \phi a_0(980))} = 0.6 \times 10^{-2}$ [BESIII, Phys. Rev D, 83, 032003 (2011)]

$f_1(1285) \to \pi K\bar{K}$ decay: tree level

$$BR(f_1 \to \pi K\bar{K})|_{exp} = (9.0 \pm 0.4)\%$$

[Particle Data Group, Chin. Phys. C, 38, 090001 (2014)]



TREE LEVEL DIAGRAMS:

Same vertices as before:

- $-it_1 = -ig_{f_1} C_1 \epsilon^{\mu} \epsilon'_{\mu}$
- $-it_2 = -igC_2(k-p)^{\mu} \epsilon'_{\mu}$

	C_1
A) B)	$-1/2$
C) D)	$1/2$
E) F)	$-1/2$
G) H)	$1/2$

	C_2
A) H)	$-1/\sqrt{2}$
B) C)	-1
D) E)	$1/\sqrt{2}$
F) G)	1

- we sum the amplitudes for the diagrams with same final state:

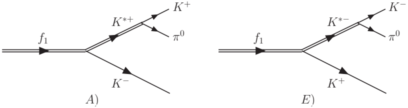
$$M^{A+E}_{\mathrm{tree}} = M^{D+H}_{\mathrm{tree}} = M_{\mathrm{tree}}$$

$$M^{B+G}_{\mathrm{tree}} = M^{C+F}_{\mathrm{tree}} = \sqrt{2}M_{\mathrm{tree}}$$

$f_1(1285) \to \pi K\bar{K}$ decay: tree level

we take diagrams A) and E) as reference

$\longrightarrow \pi^0 K^+ K^-$ **final state**



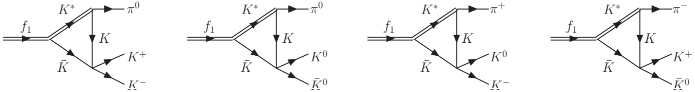
$$M_{\rm tree} = \frac{g g_{f_1}}{2\sqrt{2}}\left([(\vec{k}-\vec{p}) - \frac{m_\pi^2 - m_K^2}{m_{K^*}^2}(\vec{k}+\vec{p})]D_1 + [(\vec{k}-\vec{p}\,') + \frac{m_\pi^2 - m_K^2}{m_{K^*}^2}(\vec{k}+\vec{p}\,')]D_2\right)\cdot\vec{\epsilon}$$

- p and p' are the momenta of K^+ and K^- respectively, k is the momentum of the π^0
- $D_1 = \frac{1}{(k+p)^2 - m_{K^*}^2 + i m_{K^*}\Gamma_{K^*}}$ and $D_2 = \frac{1}{(k+p')^2 - m_{K^*}^2 + i m_{K^*}\Gamma_{K^*}}$ are the propagators of the K^*
- $\Gamma_{K^*} = \Gamma_{\rm on}\left(\frac{q_{\rm off}}{q_{\rm on}}\right)^3$ is the total width of the K^*

$f_1(1285) \to \pi K\bar{K}$ decay: FSI

now we study the **final state interactions (FSI)** by means of the **triangular mechanism**

A) $K\bar{K}$ interaction:



- rescattering $\to$ generates the $a_0(980)$ $(I=1)$
- scattering amplitude $t^{I=1}_{K\bar{K}\to K\bar{K}}(M_{K\bar{K}})$: obtained using $T=[1-VG]^{-1}V$

  [with V taken from Oller et al., Nucl. Phys. A 620, 438 (1998)]

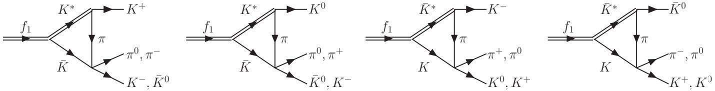
  $\longrightarrow$ good description of the $a_0(980)$ using $q_{\rm max}=900$ MeV
- we sum the four diagrams with final state $\pi^0 K^+ K^-$

$$\boxed{M^{K\bar{K}}_{\rm FSI} = -\frac{g\ g_{f_1}}{2\sqrt{2}}(2\mathcal{I}_1+\mathcal{I}_2)\ 2\ t^{I=1}_{K\bar{K}\to K\bar{K}}(M_{K\bar{K}})\ \vec{\epsilon}\cdot\vec{k}}$$

- $M^2_{K\bar{K}} = (p+p')^2 = M^2_{f_1} + m^2_\pi - 2M_{f_1}\sqrt{|\vec{k}|^2+m^2_\pi}$
- $\mathcal{I}_1$, $\mathcal{I}_2$ same as before

$f_1(1285) \to \pi K\bar{K}$ decay: FSI

B) πK interaction:



- rescattering $\to$ generates the $\kappa(800)$ ($I = 1/2$)
- scattering amplitude: $t^{I=1/2}_{\pi K \to \pi K}(M_{\pi K})$ $\to$ good description of the $\kappa(800)$ using $q_{\max} = 900$ MeV
- we sum the four diagrams with final state $\pi^0 K^+ K^-$

$$M^{\pi K}_{\rm FSI} = \frac{g\, g_{f_1}}{2\sqrt{2}}(2\mathcal{I}'_1 + \mathcal{I}'_2)\, t^{I=1/2}_{\pi K \to \pi K}(M^{(1)}_{\pi K})\, \vec{\epsilon}\cdot\vec{p} + \frac{g\, g_{f_1}}{2\sqrt{2}}(2\mathcal{I}''_1 + \mathcal{I}''_1)\, t^{I=1/2}_{\pi K \to \pi K}(M^{(2)}_{\pi K})\, \vec{\epsilon}\cdot\vec{p}'$$

- $\mathcal{I}'_1$, $\mathcal{I}'_2$, $\mathcal{I}''_1$ and $\mathcal{I}''_2$ obtained from $\mathcal{I}_1$ and $\mathcal{I}_1$ with suitable substitution of kinematic variables
- $M^{(1)}_{\pi K} = \sqrt{(k+p')^2}$ and $M^{(2)}_{\pi K} = \sqrt{(k+p)^2}$

$\Longrightarrow$ **full amplitude for the $\pi^0 K^+ K^-$ final state:**

$$M = M_{\rm tree} + M^{K\bar{K}}_{\rm FSI} + M^{\pi K}_{\rm FSI}$$

$f_1(1285) \to \pi K\bar{K}$ decay: results

TOTAL DECAY WIDTH:

$$\Gamma_{K\bar{K}\pi} = 6\frac{1}{64\pi^3 M_{f_1}} \int\int d\omega_{K^+} d\omega_{K^-} \overline{\sum}|M|^2 \,\theta(1-\cos^2\theta_{K\bar{K}})\theta(M_{f_1} - \omega_{K^+} - \omega_{K^-} - m_\pi)$$

- **factor 6** $\longrightarrow$ accounts for all the final charges: $\pi^0 K^+ K^-$, $\pi^+ K^0 K^-$, $\pi^- K^+ \bar{K}^0$ and $\pi^0 K^0 \bar{K}^0$, having weights 1, 2, 2, and 1
- ω_{K^+} and ω_{K^-} energies of the K^+ and K^-
- $\cos\theta_{K\bar{K}}$ given by energy conservation

g_{f1}	$\Gamma_{K\bar{K}\pi}$	B.R.
9687 MeV (1)	3.12	12.9%
7230 MeV (2)	1.74	7.2%

(1) Aceti et al., Eur. Phys. J. A 51, 4, 48 (2015)
(2) Roca et al., Phys. Rev. D 72, 014002 (2004)

$$BR(f_1 \to \pi K\bar{K})|_{exp} = (9.0 \pm 0.4)\%$$

$$\boxed{B.R.(f_1 \to K\bar{K}\pi) = (7.2 - 12.9)\%}$$

with $g_{f1} = 9687$ MeV and **only the tree level diagrams**: $B.R.(f_1 \to K\bar{K}\pi) = 15\%$

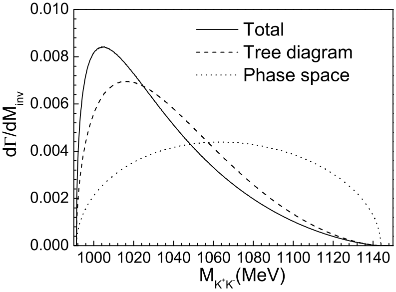
the contribution of the FSIs is very small: cancellation due to their opposite sign

$f_1(1285) \to \pi K\bar{K}$ decay: results

INVARIANT MASS DISTRIBUTION $f_1(1285) \to \pi^0 K^+ K^-$ as a function of $M_{K^+K^-}$:

$$\frac{d\Gamma}{dM_{K^+K^-}} = \frac{M_{K^+K^-}}{64\pi^3 M_{f_1}^2} \int d\omega_{K^+} \overline{\sum}|M|^2 \theta(1-\cos^2\theta_{K\bar{K}})\ \theta(M_{f_1} - \omega_{K^+} - \omega_{K^-} - m_\pi)\theta(\omega_{K^-} - m_K)$$

with $\omega_{K^-} = \frac{1}{2M_{f_1}}(M_{K^+K^-}^2 + M_{f_1}^2 - m_\pi^2) - \omega_{K^+}$



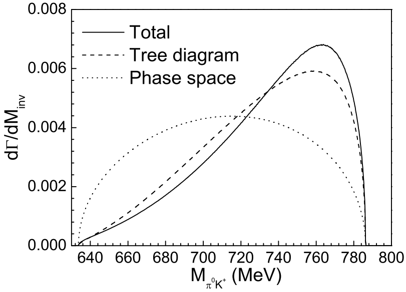
- shape of the tree level very different
- we can see a peak at low $M_{K^+K^-}$
- the peak is shifted closer to the mass of the $a_0(980)$ by the FSI

$f_1(1285) \to \pi K\bar{K}$ decay: results

INVARIANT MASS DISTRIBUTION $f_1(1285) \to \pi^0 K^+ K^-$ as a function of $M_{\pi^0 K^+}$:

$$\frac{d\Gamma}{dM_{\pi^0 K^+}} = \frac{M_{\pi^0 K^+}}{64\pi^3 M_{f_1}^2} \int d\omega_{K^+} \overline{\sum}|M|^2 \theta(1-\cos^2\theta_{K\bar{K}})\ \theta(M_{f_1} - \omega_{K^+} - \omega_{K^-} - m_\pi)\theta(\omega_{K^-} - m_K)$$

with $\omega_{K^-} = \frac{1}{2M_{f_1}}(M_{f_1}^2 + m_K^2 - M_{\pi^0 K^+}^2)$



- now the peak is at high $M_{\pi^0 K^+}$
- the peak is shifted closer to the mass of the $\kappa(800)$ by the FSI

presence of the peak
$\Longrightarrow$ tied to the K^* propagator

$\Longrightarrow$ **tied to the $\bar{K}^* K$ — $c.c.$ nature of the $f_1(1285)$**

Conclusions

The assumption that the $f_1(1285)$, $a_0(980)$ and $f_0(980)$ are dynamically generated resonances is supported by our findings:

- a branching ratio for $f_1(1285) \to \pi\eta$ in good agreement with experiment within errors
- a branching ratio for $f_1(1285) \to \pi K\bar{K}$ in good agreement with experiment within errors

We also observed:

- an amount of isospin breaking in $f_1(1285) \to \pi^0 f_0$ different from other reaction
  $\Longrightarrow$ it appears to be strongly dependent on the process
- shape of the invariant mass distributions of $f_1(1285) \to \pi K\bar{K}$ tied to the nature of the f_1
  $\Longrightarrow$**a measurement of these quantities would help understanding the nature of the $\boldsymbol{f_1(1285)}$**

The molecular $K^*\bar{K}$ nature of the $f_1(1285)$ and its decays into $\pi a_0(980)$ ($\pi f_0(980)$) and $\pi K\bar{K}$

Francesca Aceti

Instituto de Física Corpuscular, Universidad de Valencia - CSIC

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Collaborators:

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